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FLARE-LESS LONG GAMMA-RAY BURSTS AND THE PROPERTIES OF THEIR MASSIVE STAR PROGENITORS

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ABSTRACT

While there is mounting evidence that long Gamma-Ray Bursts (GRBs) are associated with the collapse of massive stars, the detailed structure of their pre-supernova stage is still debatable. Particularly uncertain is the degree of mixing among shells of different composition, and hence the role of magnetic torques and convection in transporting angular momentum. Here we show that early-time afterglow observations with the *Swift* satellite place constraints on the allowed GRB pre-supernova models. In particular, they argue against pre-supernova models in which different elemental shells are unmixed. These types of models would produce energy injections into the GRB engine on timescales between several hundreds of seconds to a few hours. Flaring activity has *not* been observed in a large fraction of well-monitored long GRBs. Therefore, if the progenitors of long GRBs have common properties, then the lack of flares indicates that the massive stars which produce GRBs are mostly well mixed, as expected in low-metallicity, rapidly rotating massive stars.

Subject headings: accretion, accretion disks - black hole physics - gamma-rays: bursts - X-rays: general

1. INTRODUCTION

Theoretical studies (e.g. MacFadyen & Woosley 1999) have suggested that long GRBs are produced by the collapse of rapidly-rotating, low-metallicity massive stars. In the last few years, the association between a GRB and the death of a massive star has found strong support through observations of supernovae associated with GRBs (Stanek et al. 2003; Hjorth et al. 2003).

Despite this progress, many details of the evolution of the massive star (and hence on its inner structure at the moment of death) are still rather uncertain. Attempts to constrain the characteristics of the GRB progenitors have been made by Campana et al. (2008). They performed a detailed study of the X-ray spectrum of GRB 060218, discovering a lower than normal O/N ratio in the surrounding of the burst progenitor. They concluded that only a progenitor star characterized by a fast stellar rotation and sub-solar initial metallicity could produce such a metal enrichment.

What remains very uncertain however is the interior structure of the pre-supernova star, and in particular the extent to which the different burning layers are mixed. This has important implications for the physics of angular momentum transport in the stellar interior, and for the relevance of magnetic fields in the stellar evolution. No direct observational constraints have been obtained so far on such quantities.

In this *Letter* we identify an observational signature in the GRB phenomenology which bears direct consequences for the structure of the pre-supernova star. The launch of the *Swift* satellite in November 2004 has opened a new window of early-time observations of Gamma-Ray Bursts (GRBs) and their afterglows. Early-time observations with the *Swift* X-ray Telescope (XRT) telescope have revealed a new and unexpected phenomenology. Nearly half of the bursts displayed erratic X-ray flares peaking on timescales between several hundreds of seconds to several hours (Burrows et al. 2005; Nousek et al. 2006; O'Brien et al. 2006; Falcone et al. 2006, 2007; Chincarini et al. 2007). The observed phenomenology has been found to be common to both long and short GRBs, and a number of studies have been aimed at establishing the origin of these X-ray rebrightenings. While in some cases the data are consistent with a refreshed (external) shock (Guetta et al. 2007), the greater majority of the flares do require an extended activity of the inner engine, due to their fast temporal rise and decay (Zhang et al. 2006; Lazzati & Perna 2007; Chincarini et al. 2007; Falcone et al. 2007) and as indicated by internal shock modeling (Maxham & Zhang 2009).

Several authors have explored ideas for producing a continued activity of the GRB inner engine after the time frame of the classical prompt emission. King et al. (2005) suggested that the X-ray flares could be produced by means of the fragmentation of the collapsing stellar core in a modified collapsar scenario. Dai et al. (2006) proposed that the flares can be created by magnetic reconnection events driven by the breakout of magnetic fields from the surface of differentially rotating millisecond pulsars produced from a binary merger. An engine that can be stopped and restarted following repeated episodes of magnetic flux accumulation and release was hypothesized by Proga & Zhang (2006). The observational properties of the flares, namely a correlation between their duration and their arrival times and an anticorrelation between their duration and their peak luminosity, together with their common existence in both long and short GRBs, prompted Perna et al. (2006) to notice that the origin of the flares is consistent with viscous evolution of several rings of material, which they suggested were produced by fragmentation or large-amplitude variability within the hyperaccreting inner disk.

Whichever the underlying reason for the flares, here we focus our attention on two important facts: *(a)* flares are observed in both long and short GRBs, and with similar properties; *(b)* more than half of the well-monitored bursts do *not* display any flaring activity[3] (this is true independently for both the long and the short class). We interpret these facts as a hint that the flaring activity is unlikely to be directly related to the progenitor structure[4]. In fact, if long and short GRBs have

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[3] Out of the 110 *Swift* bursts that Falcone et al (2007) studied, they found that only 33% of them had evidence for flares at more than the 3σ level.
[4] In the context of this work, we indicate by 'progenitor' the astrophysical

different types of progenitors, as commonly believed, then it would be hard to explain point *(a)*. Furthermore, if the progenitors of each class have similar properties, then is it not straightforward to account for *(b)*. Flares are most likely related to a common element of long and short GRBs, whose properties can display a large degree of variation from case to case.

With the above considerations in mind, we will argue here that the lack of flares in a substantial fraction of long GRBs places constraints on the interior structure of the pre-supernova star progenitor of long GRBs.

The paper is organized as follows: §2 describes the main features of the collapsar model which are critical for our discussion. These are related in §3 to the GRB phenomenology. Finally, we summarize in §4.

2. THE ANGULAR MOMENTUM STRUCTURE OF THE PRE-SUPERNOVA STAR IN DIFFERENT MODELS

The collapsar model (Woosley 1993; MacFadyen & Woosley 1999; MacFadyen, Woosley & Heger 2001, MWH01 in the following) for long GRBs has received strong support by the observation of supernovae associated with this class of GRBs (Stanek et al. 2003; Hjorth et al. 2003). The iron core of a rapidly-rotating star of mass greater than $\approx 25 M_\odot$ collapses to form a black hole at its center. The outer layers fall toward the newly formed black hole and are halted at the Kepler radius. The location of the circularization radius of the infalling material contains direct information on the angular momentum structure of the pre-supernova star, and hence on the mechanisms by which angular momentum is transferred in the interior of the evolving star.

Earlier studies of massive stellar evolution (with the exception of a few, such as Spruit & Phinney 1998 and Maeder & Meynet 2004), did not include a possibly important effect, that is the torque exerted in differentially rotating regions by the magnetic field that threads them. With all the uncertainties regarding the correct treatment of B-field generation and evolution (e.g. Rudiger & Hollerbach 2004), a first attempt to include angular momentum transport by magnetic torques in simulations of pre-supernova stars was made by Heger et al. (2005). They noted, however, that their results are quite sensitive to several uncertain model parameters, such as the efficiency of the dynamo generating the magnetic field, the effect of composition gradients, and the initial angular momentum of the star. It should also be pointed out that the standard diffusion treatment of angular momentum transport in radiative layers adopted by these authors (as well as others), fails to reproduce some basic features, such as the solar rotation profile and the Li dip in F stars. It is also at odds with helioseismic inversions (Thompson et al. 2003) and 3D numerical simulations (Miesch et al. 2006)[5]. Furthermore, and of special importance here, the inclusion of angular momentum transport by magnetic torques during the precollapse evolution is known to create problems for those stars that would become GRBs. In fact, while GRBs are believed to be produced by stars endowed with a particularly large rotation, the angular momentum transport saps the core of the necessary rotation. This problem was addressed by Woosley & Heger (2006; see also Yoon & Langer 2005). They studied the evolution of very rapidly rotating stars, and found that, for the highest possible rotation rate, a new evolutionary channel appears, in which single stars fully mix while still on the main sequence, and never become red giants. Under specific conditions, these stars (which comprise about 1% of the massive star population), could retain enough angular momentum to produce GRBs. In this scenario, the angular momentum in the interior of the pre-supernova star has a continuous distribution with radius, unlike the case in which the shells of the various burning elements are unmixed. A rather strong compositional mixing is also obtained in 2D and 3D numerical simulations of pre-SN massive star interiors that include long-distance angular momentum redistribution and convection-induced mixing by the excitation of internal waves (Meakin & Arnett 2006; 2007; see also Mocak et al. 2009 for similar findings in the context of He flash driven convection).

Given all of the uncertainties still present in the current understanding of the progenitor stars of GRBs, being able to validate the various theoretical models by means of direct observational tests is very valuable.

In the following, we will consider the observational consequences for the GRB phenomenology of different types of GRB progenitor stars.

3. IMPLICATIONS FOR GRB PHENOMENOLOGY OF THE PRE-SUPERNOVA INTERIOR STRUCTURE

If the star is fully mixed, as suggested by Woosley & Heger (2006), then the angular momentum is a continuous function of the radius r, which can be approximated as (Kumar, Narayan & Johnson 2008a)

$$j(r) \approx 3.8 \times 10^{18} M_{\rm BH}^{1/2} r_{10}^{1/2} f_\Omega(r) \ \ {\rm cm^2\,s^{-1}}\,, \qquad (1)$$

where $r_{10} = r/(10^{10}\ {\rm cm})$, $M_{\rm BH}$ is the black hole mass in units of solar masses, and f_Ω is the ratio between the angular velocity of the gas and the local Keplerian angular velocity. This model, as demonstrated by Kumar et al. (2008a; 2008b), can produce plateaus in the afterglow light curve, but the overall trend of the time evolution of the afterglow is generally smooth.

In the following, we will examine the consequences for the GRB phenomenology of the unmixed GRB progenitor models, and we will consider, as a representative example, the pre-supernova star model used by MWH01, with mass $M = 25 M_\odot$, and an equatorial rotational velocity on the main sequence of 200 km s^{-1}. While the specific details of our results are expected to vary depending on the precise location and angular momentum of the shells, our general arguments are expected to hold.

In these types of pre-supernova stars, the burning layers of different elements are unmixed, and the specific angular momentum of the various shells is different, increasing with radius. Ejected material that does not possess enough energy to unbind falls back, eventually settling at the circularization radius, depending on the value of its specific angular momentum j. While the iron core collapses to form a black hole, the outer burning shells receive a radial momentum which results in some ejecta becoming unbound. The bound material falls back, eventually settling into a ring at the Keplerian radius. From that point on, the evolution is driven by viscosity and by accretion of low angular momentum material from the polar regions.

The innermost material, close to the last stable orbit, accretes rapidly at high rates, giving rise to the prompt emission, while the outer shells start accreting at later times.

entity *prior* to the formation of a disk.

[5] A substantial improvement between theory and observations has been made by the inclusion of the transport of angular momentum by internal waves in stellar interiors (Zhan et al. 1997; Talon et al. 2002; Charbonnel & Talon 2005).

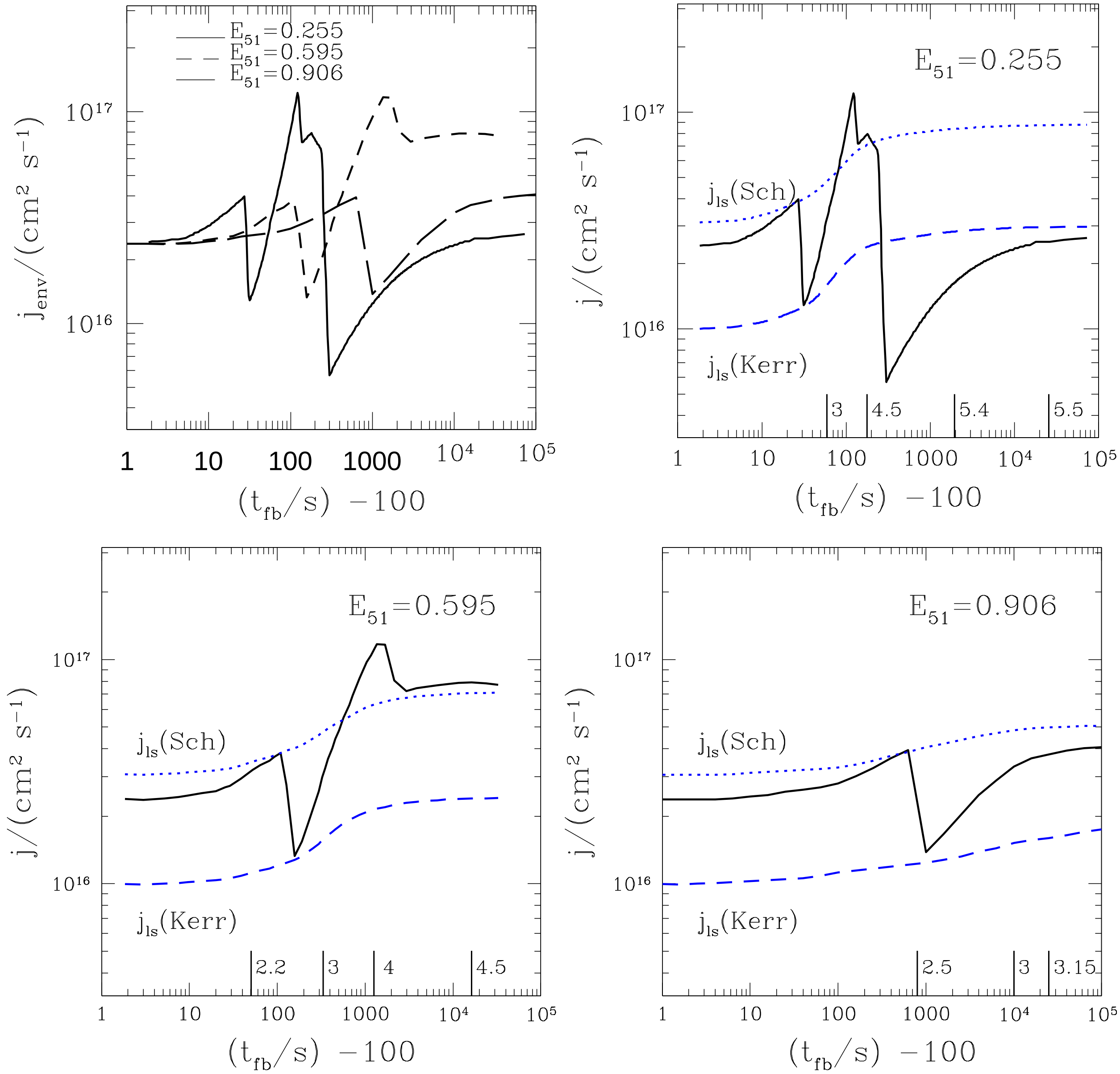

FIG. 1.— The specific angular momentum of the burning shells in the envelope of the pre-supernova star studied in MWH01 versus their fallback time $t_{\rm fb}$ after the explosion. The structure results from the evolution of a star of mass $M = 10^{25} M_\odot$ and an equatorial rotational velocity on the main sequence of 200 km s^{-1}. This model assumes no mixing between different burning layers. The top left panel compares the envelope fallback time for three different explosion energies. The other three panels compare, for each value of the explosion energy, the specific angular momentum of the shells to the specific angular momentum of a particle at the last stable orbit, in the two limits of a Schwarzschild and of a Kerr black hole. The numbers next to the vertical ticks indicate the amount of mass accreted up to that time, in units of solar mass. When t_{fb} = 100 s, a black hole of mass of $2M_\odot$ has already formed, partly from direct core collapse and partly from subsequent accretion. For a rapidly rotating black hole, as expected from the collapse of the core of the pre-supernova star under consideration, distinct episodes of accretion are expected, with the last extending to timescales of up to several hours.

There are two times which combine to produce the timescales over which the rebrightenings due to accretion from the outer shells take place. The first is the time that the ejecta take to fall back to the circularization radius after being propelled outwards. A hard limit to this is given by the free fall time

$$t_{ff} \sim \frac{1}{\sqrt{G\rho_{ave}}}, \qquad (2)$$

where ρ_{ave} is the average density of the material inside the shell under consideration. Even for the outermost shell, the dynamical time is on the order of seconds. A more realistic estimate of the fallback time must include the effects of the kinetic energy (and hence the radial velocity) that is imparted to the envelope by the explosion. The mass fallback rate for a range of explosion energies between 0.255×10^{51} erg and 1.682×10^{51} erg was computed for the model star under consideration by MWH01. In the equatorial region, which is of interest for our study, the effective energy is expected to be in the lower range.

The specific angular momentum of the envelope, $j_{\rm env}$, as a function of the fallback time is displayed in Fig.1 for the

effective kinetic explosion energies $E = 0.255 \times 10^{51}$ erg, $E = 0.595 \times 10^{51}$ erg, and $E = 0.906 \times 10^{51}$ erg (see top left panel). In order for a disk to form, $j_{\rm env}$ must be larger than the specific angular momentum $j_{\rm ls}$ of a particle orbiting at the last stable orbit. The specific angular momentum of a particle on a corotating orbit of a black hole of mass M and angular momentum $J = aM$ is given by

$$j = \frac{\sqrt{GMR}\left[R^2 - 2(a/c)\sqrt{GMR/c^2} + (a/c)^2\right]}{R\left[R^2 - 3GMR/c^2 + 2(a/c)\sqrt{GMR/c^2}\right]^{1/2}} \,. \quad (3)$$

The right top panel and the bottom panels of Fig.1 respectively show, for each of the three considered explosion energies, $j_{\rm env}$ as compared to the minimum specific angular momentum $j_{\rm ls}$ needed to form a disk at the last stable orbit, for the limiting cases of a Schwarzschild ($a = 0$) and of a Kerr ($a = GM/c$) black hole. A minimum value of $j_{\rm ls}$ (and hence of the Kerr parameter), for each explosion energy, can be derived by the condition that, at early times, $j_{\rm env} > j_{\rm ls}$, or else there would not be a disk to power the prompt GRB phase. From Fig.1 it can be seen that, if the innermost material has enough angular momentum to circularize in a disk, this will also be the case for an outer shell of the envelope. The precise location of the circularization radius will depend on the specific angular momentum of the material, as well as on that of the black hole, according to Eq.(3). For the outermost shell, we find the circularization radius to be on the order of about $10\,R_s$. Once the bound material has circularized in a ring, the following evolution occurs on the viscous timescale

$$t_{\rm visc}(R_{\rm circ}) = \frac{R_{\rm circ}^2}{H^2\alpha\Omega_K} \sim 5\times 10^{-4}\alpha_{-1}^{-1} m_3 r^{3/2}\left(\frac{R}{H}\right)^2 \ {\rm s}\,, \quad (4)$$

where Ω_K is the Keplerian velocity of the gas in the disk, H the disk scale-height, α the viscosity parameter (Shakura & Sunyaev 1973), and r the radius in units of the Schwarzschild's radius. The specific functional form of $t_{\rm visc}$ with radius depends on the properties of the disk.

If advection dominates, which is likely to be the case for very large accretion rates, then the disk scale height is $H \sim R$, and the viscous timescale at $r \sim 25$ where the outermost shell circularizes is ~ 0.04 sec. Once a new, outer ring of material catches up with the inner accreting ring, a secondary episode of accretion is likely to occur. A discussion of this enhanced, late energy output was presented by Lee, Ramirez-Ruiz & Lopez-Camara (2009) for the case in which the disk is produced by the debris of the tidal disruption of a compact object in a binary merger, and the late accretion episode derives from material further out in the tidal tail. They found that the injection of this material can re-energize the main accretion disk, as long as the fallback mass dominates over the remnant disk mass at the time at which it is re-injected at its circularization radius. The following evolution then proceeds on the viscous time of the resulting ring. Their simulations also showed that the secondary episode of accretion produces a total energy output and neutrino luminosity which are comparable to those observed in flares.

In the pre-supernova model considered here we would expect, at a qualitative level, a similar phenomenology. Given the specific angular momenta of the two shells, and the corresponding BH mass at the time they accrete, from inversion of Eq.(3), we find that the ratio between the circularization radii of the two shells varies between $R_{\rm circ}^{\rm out}/R_{\rm circ}^{\rm in} \sim 8.6$ for $a = 0.2\,GM/c$, and ~ 5.6 for $a = GM/c$. This, together with the fact that $M_{\rm out}^{\rm shell} \sim 4\,M_{\rm in}^{\rm shell}$, implies that, once the material circularizes, the accretion rates of the two shells are expected to be comparable. Hence, since the fallback time of the outer shell is $t_{\rm fb}^{\rm out} \gtrsim 10\,t_{\rm fb}^{\rm in} \gg t_{\rm visc}$, and the accretion rate of the inner shell drops as $\dot{M}_{\rm in} \propto \left(t/t_{\rm visc}\right)^{-5/3}$ for $t \gtrsim t_{\rm fb}^{\rm in}$ (MWH01), the arrival of the outer shell on the timescale $t_{\rm fb}^{\rm out}$ will produce a significant enhancement in the tail of $\dot{M}_{\rm in}$. Therefore, as long as the accretion efficiency at late times is not suppressed with respect to that at early times, we would expect that the late, massive outer shells release a luminosity comparable to that in the prompt phase. The expected phenomenology in GRBs would hence be that of powerful flares superimposed to the powerlaw decay of the afterglow, with the specific number of flares and their arrival times depending on the details of the pre-supernova structure (here we just considered one particular case).

Among all the long GRBs detected by *Swift* and well monitored after the trigger, flares have been detected in about 30% of the cases. If, as discussed in §1, we make the reasonable assumption that the properties of the pre-supernova stars that produce long GRBs are similar, then the lack of flares in the largest majority of long GRBs argues in favor of a pre-supernova model which is fully mixed, as found in the simulations by Woosley & Heger (2006) for a low-metallicity, rapidly-rotating star. A well-mixed envelope might be a likely outcome also in the He-star/BH merger scenario (Fryer & Woosley 1998), in which the GRB is preceded by a common envelope phase during which the BH enters first the H and then the He envelope of the star. The stirring accompanying the merger process is likely to wash out any shell structure within the star.

4. SUMMARY

While it has long been recognized that the collapse of a massive star under particular circumstances can produce a long GRB, what are these "particular circumstances" is still a subject of exploration. The generally important role of a high angular momentum has been widely discussed, but the detailed structure of the interior of the pre-supernova star, connected to the extent to which angular momentum transport is effective within its envelope, is still rather uncertain.

In this *Letter* we have shown that late energy injection, from several hundreds of seconds to several hours, is a common feature of a collapsar model in which the pre-supernova star has unmixed shells of burning elements. The lack of flaring activity in more than half of the well-monitored GRBs hence argues against such a model. The arguments presented here give support to a fully mixed pre-supernova, as expected for a rapidly-rotating, low-metallicity massive star.

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